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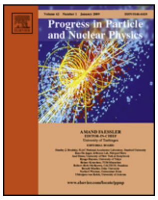

Review

Neutrino–nucleus reactions and their role for supernova dynamics and nucleosynthesis

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ABSTRACT

The description of nuclear reactions induced by supernova neutrinos has witnessed significant progress during the recent years. On one hand this progress is due to experimental data which serve as important constraints to model calculations, on the other hand it is related to advances in nuclear modeling itself and in computer hardware. At the energies and momentum transfers relevant for supernova neutrinos, neutrino–nucleus cross sections are dominated by allowed transitions, however, often with non-negligible contributions from (first) forbidden transitions. For several nuclei, allowed Gamow–Teller strength distributions have been derived from charge-exchange reactions and from inelastic electron scattering data. Importantly the diagonalization shell model has been proven to accurately reproduce these data and hence became the appropriate tool to calculate the allowed contributions to neutrino–nucleus cross sections for supernova neutrinos. Higher multipole contributions are usually calculated within the framework of the Quasiparticle Random Phase Approximation, which describes the total strength and the position of the giant resonances quite well. Both are the relevant quantities for a reliable calculation of the forbidden contributions to the cross sections.

The current manuscript reviews the recent progress achieved in calculating supernova-relevant neutrino–nucleus cross sections and discusses its verification by data. Moreover, the review summarizes also the impact which neutrino–nucleus reactions have on the dynamics of supernovae and on the associated nucleosynthesis. With relevance to the supernova dynamics, these include the absorption of neutrinos by nuclei (the inverse of nuclear electron capture which is the dominating weak-interaction process during collapse), inelastic neutrino–nucleus scattering and nuclear de-excitation by neutrino-pair emission. For supernova nucleosynthesis we discuss the role of neutrino-induced reactions for the recently discovered νp process, for the r-process and for the neutrino process, for which neutrino–nucleus reactions have the largest impact. Finally we briefly review neutrino–nucleus reactions important for the observation of supernova neutrinos by earthbound detectors.

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1. Introduction

February 1987 was the birth of extrasolar neutrino astronomy when detectors in Japan and the United States registered neutrinos which travelled over 50 kpc from the Large Magellanic Cloud to Earth and gave the first indications that a star in this neighbor galaxy of the Milky Way had exploded as a supernova [1,2]. This extraordinary scientific event also proved the general expectation that neutrinos are produced in enormous numbers in supernovae triggered by the core collapse of massive stars. In fact, about 99% of the gravitational binding energy released in the cataclysmic event is carried away by neutrinos, clearly overpowering the kinetic energy associated with the expansion of the supernova and the energy radiated away as light, despite the fascinating fact that supernovae can shine as bright as entire galaxies.

Although the neutrinos observed from supernova SN1987A were likely all electron antineutrinos, identified by the Cerenkov light produced by the relativistic positrons after a charged-current neutrino reaction on protons in the water Cerenkov detectors, the amount of observed neutrinos and their energy spectrum (of order a few 10 s of MeV) confirmed the general understanding of supernova dynamics [3]. These observations were supplemented by detailed studies of the SN1987A lightcurve, which as expected, followed the sequence of half-lives of radioactive nuclides like ^{56}Ni, ^{57}Ni or ^{44}Ti, which were copiously produced in the hot supernova environment [4].

Core-collapse, or Type II, supernovae are the final fate of massive stars, when at the end of hydrostatic burning, their inner core, composed of nuclei in the iron–nickel mass range, runs out of nuclear fuel and collapses under its own gravity triggering an explosion during which most of the star's material, partly processed in the hot environment in what is called explosive nucleosynthesis, is ejected into the Interstellar Medium [3]. In the general picture of core-collapse supernovae and their associated nucleosynthesis, neutrino reactions on nucleons and nuclei play an important role. Arguably, however, the most important impact neutrinos have on the supernova dynamics is the fact that, for the typical supernova neutrino energy scales, they virtually do not interact with matter for densities smaller than a few 10^{11} g cm^{-3}. This makes neutrinos the most efficient cooling mechanism during the late hydrostatic burning stages and the early collapse phase, where neutrinos could be thought of as free streaming with an appropriate energy loss correction for nuclear reactions mediated by the weak interaction like β decay or electron capture. This picture does not hold at higher densities, say in excess of 10^{12} g cm^{-3}, where the neutrino interaction with matter is strong enough to make a detailed book keeping of neutrinos and their interaction with matter a tedious, but necessary requirement for supernova modeling. During the collapse phase when densities larger than 10^{12} g cm^{-3} are reached, it is the elastic scattering of neutrinos on nuclei which changes the neutrino transport through the dense matter to a diffusion problem with time scales larger than the competing collapse time scale. As a consequence, neutrinos are trapped during the final stage of the collapse. By inelastic scattering on electrons and, to a lesser extent, on nuclei, neutrinos exchange energy with matter and get thermalized. Inelastic neutrino–nucleus scattering also plays an interesting role in a short episode after core bounce, where it alters the spectrum of electron neutrinos emitted during the so-called neutrino burst [5].

The supernova explosion is triggered by a shock wave which, when passing outwards through the Fe–Ni-core, dissociates the heavy nuclei into free nucleons. The interaction of neutrinos, produced by the hot matter of the newly-born neutron star in the center, with the free protons and neutrons behind the shock are an effective additional energy source which, together with effects like convection and plasma instabilities, are required for successful explosions, as modern multi-dimensional supernova simulations show [6,7].

It is also the competition between the various interactions of electron neutrinos with neutrons and of anti-electron neutrinos with protons that determines the proton-to-neutron ratio of the matter ejected from the surface of the nascent